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Radio Triggered Star Formation in Cooling Flows

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Abstract

The giant galaxies located at the centers of cluster cooling flows are frequently sites of vigorous star formation. In some instances, star formation appears to have been triggered by the galaxy’s radio source. The colors and spectral indices of the young populations are generally consistent with short duration bursts or continuous star formation for durations $\ll 1$ Gyr, which is less than the presumed ages of cooling flows. The star formation properties are inconsistent with fueling by a continuously accreting cooling flow, although the prevalence of star formation is consistent with repeated bursts and periodic refueling. Star formation may be fueled, in some cases, by cold material stripped from neighboring cluster galaxies.

1 Introduction

More than half of clusters within redshift $z \sim 0.1$ contain bright, central X-ray emission from \sim keV gas that appears to be cooling at rates of $\sim 10 - 1000 M_{\odot} \text{ yr}^{-1}$ (Fabian 1991). Commonly referred to as cooling flows, persistent accretion of this cooling material onto the bright, central galaxies in clusters (CDGs) at even a fraction of these rates would be capable of fueling vigorous star formation and the central engines generating their radio sources. Enhanced levels of cold gas and star formation are indeed seen in cooling flows (see McNamara 1997 for a review). However, the inferred star formation rates are only $\lesssim 1 - 10\%$ of the cooling rates derived from X-ray observations, and the amounts of cold gas detected outside of the X-ray band would account for $\lesssim 10^8$ yr of accumulated material. Between 60–70% of CDGs in cooling

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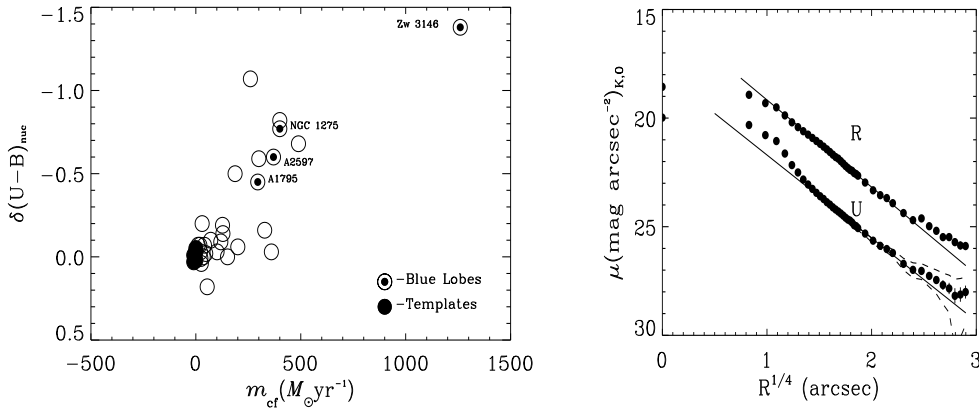


Figure 1 (left): Correlation between central $U - B$ continuum color excess and total cooling rate. Figure 2 (right): U and R surface brightness profiles for the Abell 1068 CDG. The solid lines represent a $R^{1/4}$ -law profile.

flows harbor Type 1 Fanaroff-Reiley (FR I) radio sources, while only $\sim 20\%$ of CDGs in non cooling flow clusters have bright radio sources (Burns et al. 1997). The presence of a cooling flow increases dramatically the likelihood of detecting a bright radio source in a CDG. The radio sources in cooling flows are often interacting with the cool (and hot) intracluster medium, influencing the gas dynamics (e.g. Burns et al. 1997 and this conference), and in some cases, possibly triggering star formation (McNamara 1997). The origin of the cool material, whether direct cooling from the intracluster medium, as would follow from the standard cooling flow model, or an external source, such as cold gas stripped from surrounding cluster galaxies, has not been identified conclusively. I discuss these issues in this article, illustrating several points with a brief analysis of new optical imagery for the Abell 1068 cluster CDG.

2 Host Galaxy Properties

A giant CDG resides at the base of all known cooling flow clusters. CDGs are, as a class, the largest and most luminous elliptical galaxies. Their envelopes have been traced to radii of several hundred kiloparsecs (Uson et al. 1991; Johnstone et al. 1991). The absolute magnitudes of CDGs are typically $M_V \sim -20$ to -22 within a 16 kpc radius (Schombert 1987), but they can be as luminous as $M_I \sim -26$ including the envelope (Johnstone et al. 1991).

Unusually blue colors associated with young, massive stars are often seen in the central $\sim 5 - 30$ kpc of cooling flow CDGs (McNamara 1997; Cardiel et al. 1998). The likelihood of detecting a blue population correlates strongly with \dot{m}_x . This correlation is shown using a $U - B$ color excess relative to a non-accreting galaxy template in Figure 1; it is the strongest evidence linking star

formation to the presence of a cooling flow. The star formation rates associated with the objects in Figure 1 range from $\lesssim 1 - 100 \text{ M}_\odot \text{ yr}^{-1}$ (McNamara & O’Connell 1989, McNamara 1997; Cardiel et al. 1998). Beyond the central regions, the spatially averaged surface brightness profiles usually follow the de Vaucouleurs $r^{1/4}$ law well into their halos. If the CDG has the characteristic envelope of a cD galaxy (Schombert 1987), the profile rises above the $r^{1/4}$ law extrapolated outward from the halo. In Figure 2 I show U and R surface brightness profiles for the CDG in the distant, $z = 0.1386$ cooling flow cluster Abell 1068, whose cooling rate is estimated to be $\dot{m}_x \sim 400 \text{ M}_\odot \text{ yr}^{-1}$ (Allen et al. 1995). The U -band profile rises above the $r^{1/4}$ profile in the inner several kpc of the galaxy. Beyond the inner few arcsec, both the U and R profiles follow the $r^{1/4}$ profile until reaching the cD envelope at $\mu(R) \simeq 25 \text{ mag. arcsec}^{-2}$, where the surface brightness rises above the $r^{1/4}$ profile with an amplitude of $\sim 0.5 \text{ mag}$. Apart from the blue core, this surface brightness profile is typical for cD galaxies in clusters with and without cooling flows (Porter et al. 1991). There is little evidence to suggest that the *average* halo structure and colors of cooling flow galaxies have recent star formation in excess of what is seen in non cooling flow galaxies. The blue inner regions appear to be the result of accretion concentrated onto the core of a preexisting galaxy, but evidently not throughout its volume.

3 Radio Triggered Star Formation

Most cooling flows harbor luminous $\sim 10^{40-42} \text{ ergs s}^{-1}$ emission line nebulae extending several to tens of kpc around the CDG nuclei (Heckman et al. 1989; Baum 1991). The line emission and blue optical continuum are usually extended on similar spatial scales (Cardiel et al. 1998), and the radio and emission line morphologies and powers are correlated, although with a large degree of scatter (Baum 1991, but also see Allen 1995). The tendency for strong line emission from warm, 10^4 K gas to lie along the edges of radio sources is particularly germane to understanding star formation in these objects. An early example was seen in the Abell 1795 CDG (van Breugel et al. 1984), and a more striking example is seen in $H\alpha$ imagery of the Abell 2597 CDG with the Hubble Space Telescope (Koekemoer et al. 1999). Furthermore, the radio jets in Abell 1795 and Abell 2597 bend at roughly 90 degree angles and inflate into radio lobes at the locations of dust clouds embedded in the emission-line nebulae (Sarazin et al. 1994; McNamara et al. 1996). Their disrupted (i.e. bending) radio morphologies are almost surely the result of collisions between the radio jets and cold, dense clouds associated with the line-emitting gas.

At the same time, Abell 2597 and Abell 1795 have bright blue optical continuum (blue lobes) along their radio lobes (McNamara & O’Connell 1993; McNamara 1997), much like the so-called alignment effect seen in distant ra-

dio galaxies (McCarthy 1993). That this phenomenon is seen in a relatively small sample of CDGs is particularly interesting. Unlike distant radio galaxies, the cooling flow CDGs were selected on the basis of their X-ray properties, rather than their radio properties. Upon their discovery, two models emerged to explain the blue lobes: jet-induced star formation (De Young 1995) and scattered light from an obliquely directed active nucleus (Sarazin & Wise 1993; Murphy & Chernoff 1993; Crawford & Fabian 1993). The scattered light hypothesis predicts the blue lobe light should be polarized, as is found in many distant radio galaxies exhibiting the alignment effect (Jannuzi & Elston 1991; di Serego Alighieri 1989). *U*-band continuum polarization measurements for the Abell 1795 and Abell 2597 CDGs obtained with the KPNO 4m Mayall telescope gave upper limits of $\lesssim 6\%$ to the degree of polarization in both objects, which effectively excluded the scattering hypothesis (McNamara et al. 1996; 1999).

Subsequent HST images of both objects resolved the blue lobes into knots of young star formation (McNamara et al. 1996; Pinkney et al. 1996; Koekemoer et al. 1999). The HST *R*-band image of Abell 1795’s blue knots are shown against a contour map of the radio source in Figure 3. The stellar knots are found along the edges of the radio lobes and near the collision sites of the radio plasma and cold gas. They are not found primarily along the radio jets, as would be expected if the triggering mechanism were shocks traveling transverse to the jet trajectory, as predicted in jet-induced star formation models (De Young 1995; Daly 1990, Begelman & Cioffi 1989). The observations suggest that momentum transferred through direct collisions between the radio plasma and cold gas clouds may be a more suitable triggering mechanism. (D. De Young pointed out that the strongest shocks would occur at the point of impact, and these shocks provide a possible triggering mechanism.)

Although star formation at rates of $\sim 10\text{--}40\text{ M}_\odot\text{ yr}^{-1}$ appears to be occurring in these objects, the radio sources may not have triggered all star formation. In addition to the blue light along the radio lobes, a more diffuse blue component that accounts for more than half the blue light is seen. Therefore, the radio source may be augmenting star formation in preexisting star bursts.

4 A Burst Mode of Star Formation in Cooling Flows

Tracing the history of a stellar population, even in isolation, is difficult. The problem is further complicated when the population is embedded in a bright background galaxy. The blue lobes in the Abell 1795 and Abell 2597 CDGs are the first clear-cut evidence for a burst mode of star formation in cooling flows. The blue lobes cannot be old because the alignment between the radio and optical structures can last only a fraction of the radio source lifetime and the

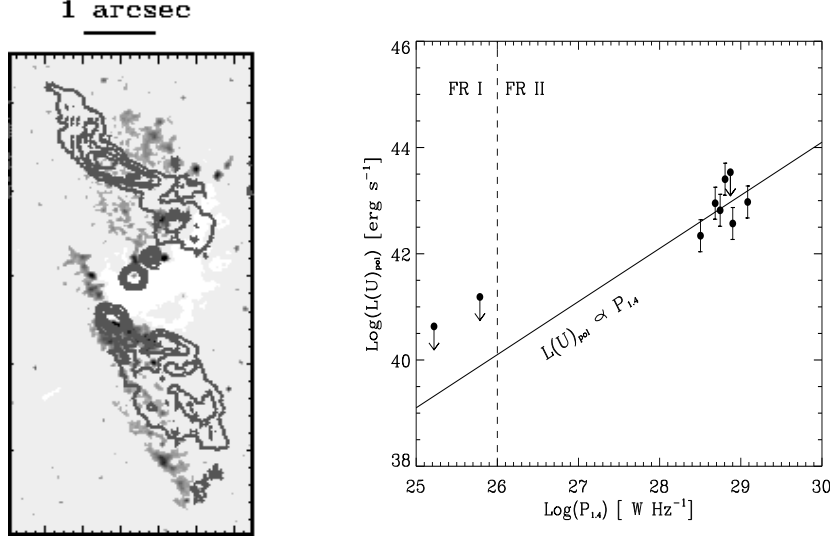


Figure 3 (left): HST image in V+R of Abell 1795’s blue lobes (greyscale) resolved into knots of star formation along the 3.6 cm radio lobes (contours). Figure 4 (right): Radio power plotted against the polarized luminosity for alignment effect radio galaxies. The 3C radio galaxies are grouped to the upper right, and the upper limits to the polarized luminosity for Abell 1795 and Abell 2597 are to the lower left of the plot. The solid line, normalized to the median of the 3C points, represents $L(U)_{\text{pol}} \propto P_{\text{rad}}$. The vertical dashed line indicates approximately the transition between FR I and FR II radio luminosities.

stellar diffusion time scale, both $\sim 10^7$ yr. Additional evidence supporting a burst mode of star formation in cooling flows has accumulated in recent years. Cardiel et al. (1998) have argued using the Mg II absorption line index, the 4000 Å break, and far UV colors that short duration bursts ($\lesssim 10^7$ yr) or constant star formation with ages $\ll 1$ Gyr best fit Bruzual model isochrones. While acknowledging the large uncertainties in the population isochrones, a burst mode of star formation is unexpected in simple, continuous cooling flow models (e.g. Fabian 1991). If star formation is indeed being fueled by cooling flows, it would seem that gas is not accreting continuously. Transient sources of fuel, such as mergers or stripping, may also be contributing.

5 Are CDGs in Cooling Flows Low Radio Power Siblings of High Redshift Radio Galaxies?

The premise that blue lobes are sites of star formation is supported by several facts. The absence of a polarized signal from the blue lobes effectively excludes the scattered light hypothesis. Synchrotron radiation can be excluded by the

absence of a detailed correlation between the radio source and blue lobes, and the nebular continuum is insufficiently strong to account for the blue color excesses. However, Balmer absorption is seen in the spectra of some objects (Allen 1995), and the emission line luminosities and H II region characteristics are often consistent with powering by young stars (Shields & Filippenko 1990; Voit & Donahue 1997), so star formation is almost certainly the primary source of the color excesses in CDGs. The situation is more complex in the high redshift powerful radio galaxies (HzRGs) exhibiting the alignment effect. The aligned optical continuum in HzRGs is often strongly polarized, which has been interpreted as the signature of scattered light from an obliquely-directed active nucleus (di Serego Alighieri et al. 1989; Jannuzi & Elston 1991). In Figure 4, I plot our polarized flux upper limits for the blue lobes in Abell 1795, Abell 2597, and the alignment regions of several HzRGs against rest frame 20 cm radio power (see McNamara et al. 1999). The polarized fluxes are measured in the rest frame U -band, and can be compared directly. Although the HzRGs are 2–3 orders of magnitude more powerful in their radio and polarized fluxes, a linear extrapolation downward between radio power and polarized flux from the mean HzRG value to the cooling flows would predict a lower polarized flux than is observed. Assuming similar host galaxy properties and scattering environments in both types of object, and further assuming the polarized flux scales approximately in proportion to radio power (see McNamara et al. 1999), at the precision of our measurements, we should not have detected a polarized flux in Abell 2597 and Abell 1795. In addition, it would seem that the polarized fluxes of HzRGs generally account for a large but incomplete fraction of the blue light, and occasionally unpolarized star light dominates (e.g. van Breugel et al. 1998). It is possible then that the blue lobes in cooling flows and the alignment effect in powerful radio galaxies are similar phenomena. But while starlight dominates the aligned continuum in lower radio power CDGs, scattered light dominates in HzRGs owing to their more powerful nuclei (McNamara et al. 1999).

6 An Analysis of New Imagery for the Abell 1068 CDG

In this section I discuss new optical imagery of the Abell 1068 central cluster galaxy. The data provide new clues to the relationship between star formation and the radio source, and raise new questions regarding the mechanism fueling star formation. U -band CCD imaging is the most sensitive means of isolating and studying the bluest galaxy populations from the ground. The blue populations in CDGs often contribute more than half of the central U -band light, while the fraction decreases to $\sim 10\%$ or less in the R and I bands. The blue populations can therefore be isolated by modeling and subtracting the background galaxy leaving the blue regions in residual. By doing so in two or

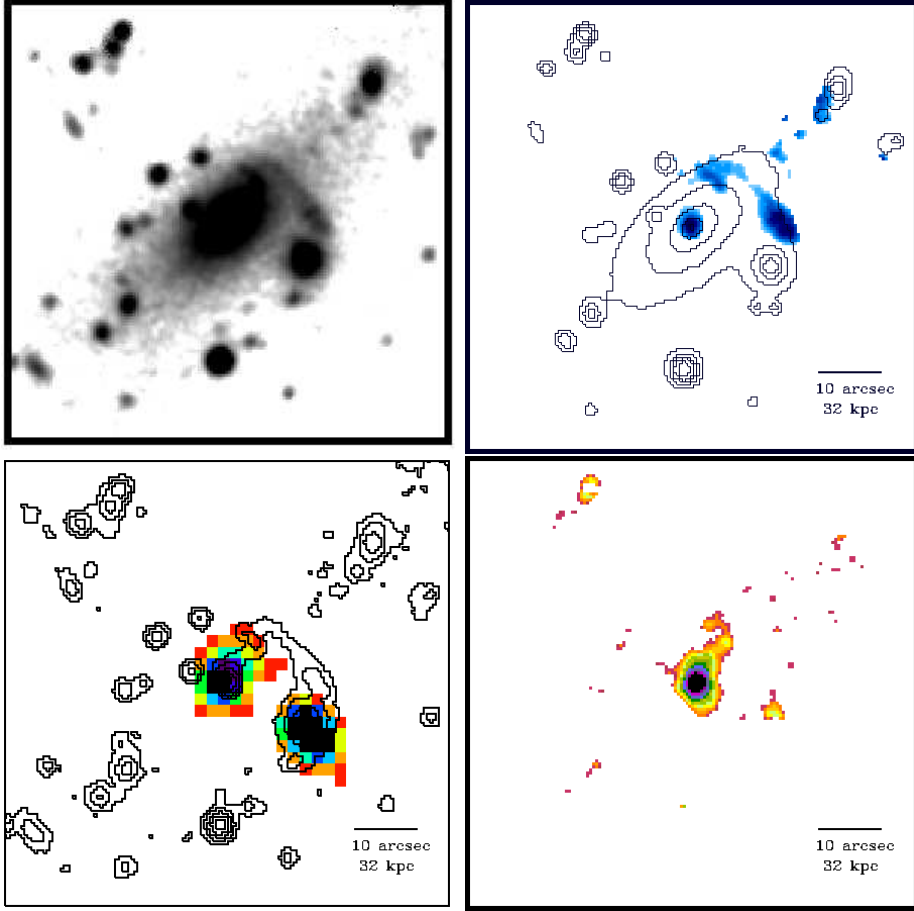


Figure 5: Imagery of Abell 1068: U -band image (upper left); $U - R$ color map (grayscale) superposed on R -band contours (upper right); U -band contours, after subtracting a smooth U -band model CDG galaxy, on the 20 cm FIRST radio grayscale image (lower left); $H\alpha$ map (lower right). The panels are registered to the same scale; north is at top and east is to the left.

more pass bands, intrinsic colors of the blue population can be estimated.

I applied this procedure to the $z = 0.1386$ Abell 1068 CDG, one of the most distant and largest cooling flows ($\dot{m}_x \sim 400 M_{\odot} \text{ yr}^{-1}$) discovered in the *ROSAT* All Sky Survey (Allen et al. 1995). It is also one of the bluest CDGs in my sample. Figure 5 presents 4-panels showing the U -band image to the upper left, a $U - R$ color map (grayscale) superposed on R -band contours to the upper right, U -band contours, after subtracting a smooth U -band model CDG galaxy, on the 20 cm FIRST radio grayscale image ($FWHM = 5.4$ arcsec), lower left, and an $H\alpha$ map, lower right. The panels are registered to the same scale; north is at top and east is to the left. Gray regions in the color map are abnormally blue.

Several features are noteworthy. First, the central region within a 13 kpc diameter is $\sim 0.5 - 0.9$ mag bluer than normal. The nuclear colors, after K

correction, range between $(U - R)_{K,0} \simeq 1.5 - 2.3$ (the foreground reddening is negligible). An arc of blue light lies 8 arcsec (25 kpc) in projection to the north-west of the nucleus, and a large wisp or arc of blue light extends to the south-west, until meeting a bright blue patch of light 13 arcsec to the east of the nucleus, and about 8 arcsec to the north of the bright neighboring galaxy to the south-west of the nucleus. This feature is nearly as blue as the nucleus with $(U - R)_{K,0} \simeq 1.6$. Finally, several blue knots, 15–30 arcsec north-west of the nucleus, appear along a line between the nucleus and a disturbed galaxy 35 arcsec to the north-west of the nucleus. The remaining colors of the off-nuclear features range from $(U - R)_{K,0} \simeq 2.0$ to the normal background color $(U - R)_{K,0} \simeq 2.4$.

After subtracting a model galaxy from the U and R CDG images, I find an intrinsic nuclear blue population color $(U - R)_{K,0} \sim -0.2$. This color is consistent with Bruzual-Charlot population model colors for a $\sim 10^7$ yr old burst population or continuous star formation for ~ 0.1 Gyr. The colors are bluer than expected for star formation in a cooling flow that has been accreting continuously for $\gtrsim 1$ Gyr. The accretion population’s luminosity mass is $\sim 2 \times 10^8 M_\odot$, which would correspond to a star formation rate of $\sim 80 M_\odot \text{ yr}^{-1}$. The off-nuclear colors, being a few tenths of a magnitude redder than the nuclear colors, are consistent with a several 10^7 yr old burst or continuous star formation for $\lesssim 1$ Gyr.

The off nuclear blue regions are apparently not in dynamical equilibrium. They appear to be stripped debris, possibly from the bright neighboring galaxies to the north-west and south-west of the nucleus. The disturbed appearance of the north-west galaxy’s R -band isophotes support the stripping hypothesis. The blue regions are considerably bluer than their putative parent galaxies, which would be consistent with blue material being composed primarily of young stars that formed out of cold material stripped from the galaxies.

6.1 *Radio Triggered Star Formation in Abell 1068?*

Both the Abell 1068 CDG and the bright galaxy to the south west of the CDG are radio sources. Each have radio powers of $\sim 8.5 \times 10^{24} \text{ W/Hz}$, which are typical for FR I radio sources. In addition, the nucleus is embedded in a luminous emission line nebula with an $H\alpha$ luminosity $\gtrsim 2 \times 10^{42} \text{ ergs s}^{-1}$ (Allen et al. 1992). Although only a low resolution radio map is available, the radio source appears extended to the north-west in the same direction as a tongue of $H\alpha$ emission extending from the nucleus. Both the radio source and the tongue of $H\alpha$ emission terminate 8 arcsec (25 kpc) to the north-west of the nucleus at the location of the bright blue arc. Such a close spatial relationship between the radio source, nebular emission, and knots of star formation are common

in powerful radio galaxies in general, and in cooling flows in particular. It is tempting to speculate that, with high resolution radio maps in hand, the radio and optical morphologies will again be consistent with radio triggered star formation in the blue arc to the north-west, much like Minkowski's Object (van Breugel et al. 1985).

7 The Fueling Mechanism

The origin of the material fueling star formation is of fundamental interest. A cooling flow origin is supported by the correlation between central blue color excess in CDGs and the cooling rate of the intracluster gas, derived independently from X-ray observations, shown in Figure 1 (e.g. McNamara 1997; Cardiel et al. 1998). Were major galaxy mergers supplying the fuel, this correlation would be difficult to explain. I would then expect CDGs experiencing significant bursts of star formation to be observed with equal frequency in cooling flow and non-cooling flow clusters alike, but they are not. Nonetheless, the evidence supporting periodic bursts of star formation implies an intermittent source of fuel. Ram pressure stripping of cold gas from neighboring cluster galaxies may be such a source of fuel, and might account for the \dot{m}_x -blue color correlation. The cooling rate $\dot{m}_x \propto \rho_{\text{gas}}^2$, and the ram pressure force on a parcel of gas is $\rho_{\text{gas}} v^2$. Therefore, the dense cooling flow regions provide a large stripping cross section capable of sweeping cold, dense molecular gas from cluster dwarf galaxies and spirals, which would rain onto the parent CDG. Abell 1068 may be a case in point, as might the Abell 1795 CDG (McNamara et al. 1996).

8 Cooling Flows and the Chandra X-ray Observatory

As I wrote this article, Chandra was launched and began sending astonishingly crisp images of cosmic X-ray sources. During the next few years, many of Chandra's targets will be clusters of galaxies, and the cooling flows promise some of the most interesting and productive cluster science. Their bright cores—the characteristic signature of a cooling flow—afford Chandra the opportunity to take full advantage of its nearly perfect, half arcsecond mirrors. For the first time, we will be capable of mapping structure in the X-ray-emitting gas on angular scales smaller than the radio sources and star formation regions. The temperature and density maps on these small scales will provide local cooling rates that can be compared directly to optically-derived star formation rates. Perhaps more than any other X-ray telescope planned or in queue, Chandra will advance our understanding of the dynamical and thermal state of cluster

cores, which hopefully will bring the long-standing cooling flow problem to resolution.

9 Summary

- Unusually blue colors associated with young, massive stars frequent the central regions of cooling flow CDGs. The probability of detecting a blue population increases sharply with \dot{m}_x derived from X-ray observations.
- Star formation in cooling flows apparently occurs in repeated, short duration ($\lesssim 1$ Gyr) bursts, not continuously as would be expected in standard cooling flow models.
- Bursts of star formation are often triggered by the radio sources.
- Cold material stripped from neighboring galaxies may feed the the radio source and fuel some star formation in CDGs.

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